GEOLOGIC MAP OF THE LERNA REGION (Ji-4) OF IO

INDEX TO MAPPING SOURCES

The rendition of features on this map was controlled by

reference to the primary source pictures outlined above.

Supplemental source images used during the compilation

are listed separately. Copies of various enhancements of

these pictures are available from National Space Science

Data Center, Code 601, Goddard Space Flight Center,

QUADRANGLE LOCATION

Number preceded by I refers to published geologic map

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INTRODUCTION

Io is the innermost of the Galilean satellites of Jupiter. Io's radius of 1,820 km and density of 3,530 kg/m³ are about the same as those of Earth's Moon. However, unlike the Moon's surface, which is largely covered by impact craters and basins, the surface of Io is dominated by volcanic landforms (Schaber, 1980, 1982). Moreover, the two 1979 Voyager encounters revealed that Io's volcanoes were actively emitting materials (Morabito and others, 1979), a process that had been predicted prior to image acquisition (Peale and others, 1979). Of the nine active eruptions identified on Voyager 1 images, eight were also active at the time of the Voyager 2 encounter 4 months later. Two additional eruptions were identified as having taken place between encounters (McEwen and Soderblom, 1983). Furthermore, 88 sites of active or recently active volcanism have been identified (McEwen and others, 1985) on the basis of an association between calderas and areas of low albedo (<0.3 in all visual wavelengths). Earth-based observations (Goguen and others, 1987) indicate that Loki Patera (lat 13° N.,

long 309°) was still active in 1985, 6 years after the Voyager encounters. Volcanic activity is so extensive on Io that not a single impact crater is recognized in the highest resolution Voyager images (about 2 km/line pair; Smith and others, 1979). Io's average surface age, inferred from the burial rate of impact craters, is probably less than 106 years (Johnson and Soderblom, 1982). As a consequence, surface features of Io are ephemeral and are therefore expected to have changed by the time of future imaging

lo's surface chemical composition appears to differ from those of the terrestrial planets, and it has been a subject of controversy. The spectacular coloration of the surface revealed in the early images led Sagan (1979) to suggest that features resembling terrestrial lava flows might be composed of sulfur. However, Clow and Carr (1980) pointed out that the rheological properties of sulfur are such that it could not support features having an estimated surface relief of nearly 10 km, and Carr (1986) argued that the near-surface materials are composed primarily of silicates. The vivid and contrasting colors—bright reds, black, and orange—depicted on the early images of Io were later shown not to be the true colors of the surface (Young, 1984, 1985; McEwen and others, 1985; McEwen, 1988); the average surface color is pale yellow similar to that in figure 1. Young (1984) has argued that either the features on lo are not composed of guenched sulfur, as the early color images would suggest, or some mechanism other than quenching is required to permit the survival of the different colors of sulfur. He suggested iron compounds as a possible alternative. Sulfur dioxide frost is known to cover most of the surface of Io, but many other materials could be represented according to the available spectral data for the remaining areas (for examples, see McEwen and others, 1985). The presence of sodium and potassium in the clouds surrounding Io (Morrison, 1982) suggests a surface

source for these volatiles. Work is currently in progress to determine many substances' spectral characteristics under conditions similar to that of the satellite's surface (an ambient surface temperature of <135 K and an atmospheric pressure of <10-7 bar). At present, many investigators, including Schaber (1982) and Greeley and others (1984), appear to have adopted a compromise whereby the magmatism on Io is envisaged as producing a mixture of silicate and sulfur materials. Conventional planetary photogeologic techniques defined by Wilhelms

of 2 to 20 km/line pair proved particularly helpful in defining units. Because impact craters are absent, stratigraphic ages were established only by superposition, intersection, and degree of degradation of volcanic units. The areal separation of some of the units precludes unique determination of their relative ages. In some places, boundaries between units of apparently different ages have been mapped, but it was impossible to determine which is the older unit. This problem is particularly true of the plains units. Images are available for the region between long 60° and 230°, but their resolution is too low to permit unique identification of landforms. (See resolution diagram.) Nevertheless, this region appears dominated by

> boundaries of the ring feature have led to the suggestion that it may be of tectonic origin (McEwen and others, 1985). Two areas that overlap part of the Lerna region were imaged at resolutions of 2 km/line pair or higher and thus can be mapped at scales larger than that of Lerna. The first area includes Maasaw Patera and extends from lat 35° S. to 48° S., long 335° to 350°; it was mapped at 1:1,000,000 scale (Moore, 1987). The second area includes Kane Patera and extends from lat

landforms similar to those in the mapped region. It is, however, distinguished

from the mapped region by the presence of "the south pole ring"—an area of

low albedo and elevated temperatures some 1,000 km in diameter centered

at about lat 75° S., long 140° (McEwen and others, 1985). The sharp

(1972) were applied to the Voyager images of Io. Color images at resolutions

 15° S. to 50° S., long 355° to 20° ; it is being mapped at 1:2,000,000 scale (W.E. Elston and F.R. Karner, work in progress). **GENERAL GEOLOGY**

PLAINS AND PLATEAU MATERIALS

Materials of the Lerna region were mapped as dark-brown to black plains deposits by Masursky and others (1979). The oldest unit in the region is considered to be the plateau material (unit pl). Unlike most other units, it contains ridges and grabens of tectonic origin, which apparently originated before the other materials were emplaced. The plateau material forms areas of elevated relief bounded by high scarps. The largest continuous expanses of plateau material form Nemea Planum (about 3.5X105 km2 in area) and Dodona Planum (about 1.25X10⁵ km²).

The plateau material appears to have been eroded to some degree everywhere in the Lerna region, particularly in the area around lat 72.5° S., long 330°. McCauley and others (1979) suggested that the erosion was caused by sulfur dioxide sapping. In some places, sapping does indeed appear to have occurred, notably where high-albedo deposits appear to originate from the base of plateau-bounding scarps. However, lack of debris at the base of the scarps is difficult to explain by a sapping process: the material of the plateau is sufficiently strong to support scarps as much as 1,700 m high, yet no debris is seen at their bases. Alternatively, Mouginis-Mark and others (1984) suggested that subsequent lava flows eroded the plateau material. Evidence for this type of erosion is the alignment of erosional remnants of the plateau unit at lat 72° S., long 320° (Voyager 1 picture number 0147J1+000); these remnants are several times longer than wide. Additional evidence for erosion by lava is seen in a channellike feature at lat 80° S., long 20°. Sublimation also may have contributed to sculpturing of the plateau material, but we would expect the resultant landscape to be similar to the etched and pitted terrain of Mars, where sublimation of carbon dioxide ice has been invoked as a landscape-forming process (Carr, 1981). The two landscapes, however, are not similar. Where the plateau material has been less eroded, it is characterized by

generally smooth and featureless surfaces except where crossed by grabens and ridges. At least five distinct topographic levels of the plateau unit can be recognized, in places forming a steplike topography. The different topographic levels probably mark stratigraphic boundaries between subunits of contrasting physical properties, which have been differentially eroded. This interpretation is supported by the observation that vertical relief of some scarps changes as little as 20 m over distances of 50 km or more (Schaber, 1982, fig. 15.12).

We suggest that the plateau material may have originally been continuous across the entire Lerna region and that the unit has been eroded back to its present form by a combination of sapping and fluid or thermal erosion. The plateau material is probably pyroclastic deposits, because (1) its surfaces are generally featureless, (2) it is distributed over areas exceeding 105 km2, and (3) it shows apparently horizontal stratification. Such a composition is supported by the dramatic visual evidence of the 250-km-high, 1,000-km-diameter eruption plumes that have been observed on Io. Low-viscosity flows erupted at high rates are another possibility, because they would produce a landscape of similar morphology.

The plains materials have generally featureless surfaces of uniform albedo and occupy large, low areas between paterae. Because the plains units contain circular depressions as deep as 2 km, Clow and Carr (1980) suggested that these units are composed of material of high yield strength. The plains materials are interpreted to be polygenetic, composed of a varied mixture of flow and pyroclastic deposits that cannot be assigned to any specific eruption center. The older plains material (unit p₁) lacks lobate outlines but contains curvilinear features of unknown but possibly tectonic origin. The younger plains material (unit p_2) has distinct lobate boundaries suggesting little modification since emplacement. If the curvilinear features in the older unit are indeed tectonic, their absence in the younger unit substantiates that unit's age assignment. The undivided plains material (unit p) is mapped in areas where evidence for age relations is lacking.

The mountain material (unit m) is characterized by relief that locally exceeds 9±1 km (Schaber, 1982) and by extremely rugged surfaces of alternating ridges and troughs. Some mountains, such as Haemus Montes, have associated craters; others, such as Silpium Mons, do not. Euboea Montes exhibit evidence of downhill motion of the mountain surface material (Schaber, 1982); the characteristics of flowage, such as high, steep, lobate flow fronts, indicate that the material has a high yield strength (Moore, 1987). The high relief and high yield strength indicate that the mountains are more likely to be composed of silicates than of sulfur.

CONE AND MOUNTAIN MATERIALS

The mountain material was suggested by Smith and others (1979) to be a part of the silicate subcrust protruding through a dominantly sulfur layer. This interpretation was questioned by Whitford-Stark (1982a), who proposed hat some mountains are volcanoes younger than, and superposed on the plateau material. The mountains are apparently of diverse ages, but their isolated occurrences preclude an age assignment relative to ages of other map units. If, as we suggested above, the plateau material was originally continuous, Haemus Montes must postdate its erosion, because they rest directly on plains material. Unfortunately, the west edge of Haemus Montes, where the plateau and mountain materials are juxtaposed, is at the terminator, and we cannot determine which overlaps the other. At Euboea Montes, the mountain material overlaps several terraces of the plateau material. If the mountain material there is a primary deposit, it must be younger than the plateau material. Alternatively, the mountain material may have been emplaced by slumping (Moore, 1987). The formation of the mountain material is poorly constrained in time; it may span the entire period of lo's interpretable history.

The only occurrence of cone material (unit c) in the region is a small conical feature at lat 71° S., long 296°. It has a summit depression and may be a volcano, but it is not associated with any materials obviously indicative of a volcanic eruption, such as surrounding lava flows or tephra.

FLOW MATERIALS The large extent of many flows indicates their emplacement as lowviscosity fluids. Calculation of the volumes of the flows is not possible because their thicknesses are unknown. Some flows, however, rival in area the largest terrestrial flood basalts and pyroclastic sheets.

The medium-albedo and light interpatera flow materials (units fim and fil, respectively), which form a large part of Lerna Regio, are distinguished purely on the basis of albedo. (Because colors differ within individual flows, color boundaries do not necessarily reflect flow boundaries.) These units cannot be related to a specific source, but the caldera at lat 70° S., long 280° is a likely candidate. All of the patera materials appear to be associated with individual

paterae. Where mutual superposition relations are clear, the materials are mapped as older (unit fp₁) or younger (unit fp₂); elsewhere, the material is mapped as undivided (unit fp). Lobate flows radiate outward in all directions from Kane Patera. However, colors of the patera at lat 70° S., long 280° are concentrically arranged, suggesting radiating flows that are possibly topographically subdued; image resolution is insufficient to detect lobate flow boundaries. The flow from Nusku Patera, however, exhibits no evidence for multiple flow units, but rather it appears to be a single large flow. The fissure material (unit ff) is dark relative to its immediate surroundings; most exposures are small (about 80 km long) and have lobate

The colors and color patterns of the flow materials indicate that they were emplaced either as sulfur flows or as silicate flows with a surface coating of sulfur-rich materials (Pieri and others, 1984). Alternatively, with the possible exception of the fissure material, many of the flows might be of pyroclastic origin. Pyroclastic flows are morphologically similar to lava flows and can mount topographic rises. Also, the "auras" (high-albedo halos) seen around some of the flows elsewhere on Io (Baloga and others, 1983, and described below) may result from jetting of fines at the forward edge of pyroclastic flows, a feature common to terrestrial examples such as

FLOOR MATERIALS Each deposit of the patera materials is surrounded by an approximately circular to elliptical, inward-facing boundary scarp or scarp segments, forming paterae interpreted as calderas. Their floors are typically 1.5 to 2.5 km below the level of their rims (Davies and Wilson, 1987). Some paterae are very large: for instance, the floor material of Creidne Patera occupies an area of 8,000 km², roughly four-fifths the area of the Big Island of Hawaii. Patera floor materials are subdivided into generally light (unit pfl), dark (unit pfd), and undivided (unit pf) deposits. (The first two designations represent a fairly wide spectrum of albedos and are only locally applicable;

Santiago Volcano, Chile (Walker, 1983).

Figure 1. False-color image of area near south pole of Io. Heavily dissected plateau can be seen in lower central

Image generated by A.S. McEwen.

part of image. South of the plateau are two low-albedo fissures. Scale about two-thirds that of geologic map.

that is, a light unit in one patera may have the equivalent albedo of a dark unit in another patera.) The undivided material makes up the floors of paterae that are uniformly colored or that were imaged at an angle so oblique that shadows masked the floor.

ATLAS OF JOVIAN SATELLITES

LERNA REGION (Ji-4) I-2055

GEOLOGIC SERIES

Hot spots were determined by the Voyager 1 infrared interferometer spectrometer (IRIS) to be associated with some patera floors (Pearl and Sinton, 1982). Later investigations (McEwen and others, 1985) showed that the hot spots are specifically associated with the dark parts of the patera floors. Even though the composition of the material forming the floors has not been uniquely determined, the proportion of the floor covered by dark material may be used as an indicator of the floor's relative age; that is, floors that are completely covered by dark material are younger, whereas those covered by light material are older. Where dark material occupies but a small part of the floors, it is commonly close to the bounding walls (for example, at Bochica, Nusku, Inti, and Viracocha Paterae), perhaps indicating higher heat flow from vents along bounding scarps.

Except where circular depressions occur on mountains, paterae do not appear to be associated with pronounced shields. We noted above that at Kane Patera, individual lobes of the patera flow materials radiate outward from the patera in all directions, indicating that the patera surmounts a topographic rise. Almost all the other paterae appear to be incised into level terrain or to lie on shields whose topographic relief is barely discernible (Wood, 1984; Moore and others, 1986). Thus these paterae may have formed by collapse without construction of a topographic edifice. The lack of significant topographic relief is typical of large terrestrial volcanoes that have

been the source of ignimbrites (Aldis and Ghazali, 1984). Although the paterae do not appear to be preferentially aligned, patera centers in the plains are spaced, with remarkable consistency, about 250 km

proposed for the Tharsis region of Mars (Whitford-Stark, 1982b), because Io's lithosphere is probably about 8 to 100 km thick (Carr, 1986). The fissure floor material (unit fi) occurs at lat 49° S., long 305°. It is composed of at least four discrete parts having an overall length of more than 150 km and a width of about 2 km. The material is detectable by its very low albedo and the highly contrasting flows that surround it. A second and similar feature at lat 46° S., long 348° is about 40 km long and 15 km wide and could be interpreted as an elongate patera, like the plume source of Loki (lat

apart. This spacing does not likely reflect the magma source depth, as

MANTLING MATERIAL Mantling material (unit ma) has a very low albedo and forms a thin deposit that does not mask the underlying topography. The unit occurs mainly around Babbar Patera (centered at lat 39° S., long 272°), a major hot spot in the adjacent Ruwa Patera quadrangle. The unit has been interpreted by McEwen and others (1985) as cooling pyroclastic deposits.

18° N., long 300°-307°, northeast of Loki Patera).

At least three types of bright halos are found on color images of the Lerna region (fig. 1). Baloga and others (1983) have suggested that bright halos, which they call "auras," around lava flows on Io were produced when the flows initiated volatile release from the underlying regolith. The darkest type is found around some paterae and around point sources within some paterae. These halos are generally greenish brown and tend to decrease in intensity at their outer edges, gradually merging with the background. This type of halo is interpreted as particulate or gaseous material in an active plume or as the deposits from a plume that became inactive immediately before the Voyager flybys. Such halos are associated with Aramazd (fig. 1) and Mithra Paterae. Accordingly, we interpret these paterae to be some of the youngest geologic features in the Lerna region. The second type of bright halo is much smaller and brighter and tends

to occur at the base of scarps or at point sources along patera walls. Individual halos range from fan-shaped to elliptical and are as long as 70 km. Halos from closely spaced sources tend to merge, disguising their individual plumelike outlines. Particularly conspicuous halos occur at scarp bases along the edge of Nemea Planum and are also associated with paterae, especially Creidne. This type is believed to result from the near-surface flow of gaseous or particulate matter. Lee and Thomas (1980) suggested that some plumelike outlines of this type result from the interaction between local vent eruptions and surface gases produced by the large plume eruptions such as Pele.

A third type of bright halo surrounds and mimics the outline of Haemus es. I his halo is similar in brightness to the second tupe of halo and is blue gray on the color image (fig. 1). We suggest that this halo could result from the regolith degassing (Baloga and others, 1983) noted above; here the degassing may have been initiated by pressure exerted by the mass of the

Circular dark halos around point sources appear to be either particulate material above active vents or deposits from recently active vents such as those at Nusku, Heno, and Mithra Paterae. None of these calderas were identified as active by McEwen and others (1985), so the dark halos may well be surficial deposits. Elongate dark areas, such as those around the base of Haemus Montes (inside the bright halo), appear to be low-albedo equivalents of the second type of bright halo; they may have originated in a similar manner but may differ in composition. STRUCTURE

The dominant structural elements in the Lerna region are grabens. Some are longer than 400 km; they have fairly constant widths of about 2 km except where widened by erosion. Grabens are confined almost exclusively to the plateaus and, to a large degree, they have controlled the erosion of the plateau material. At the west end of Nemea Planum, a graben set trending N. 45° E. intersects a set trending N. 45° W., forming an orthogonal network. On Earth's Moon, a similar orthogonal network known as the "lunar grid" has been ascribed to several causes, including tidal stresses (Gash. 1978). Likewise, Schaber (1982) has suggested that the grabens on Io may result from tidal flexing of the satellite. If so, tidal flexing has been more efficient in the past than at present, because the grabens are absent on the younger units. Also (or alternatively), the plateau material may possess considerably more cohesive strength than the other units, so that it deformed by brittle fracture rather than ductile flow. A third alternative is that the smooth units are so young that they have not yet developed grabens. Other graben sets within the plateau material trend N. 80° W., N. 80° E., and N. 60° E. The significance of these trends is unknown. Other structural elements on Io include fault scarps around paterae and

at the south end of Euboea Montes and ridges, also largely within plateau material, particularly north of Nusku Patera and on Pan Mensa. **GEOLOGIC HISTORY**

The earliest event still decipherable in the Lerna region was the production of the plateau material, possibly as large pyroclastic deposits from unidentified sources. The region was then subjected to tension, resulting in the formation of horsts and grabens. The plateau was subsequently eroded, and lava flows and pyroclastic materials were emplaced by volcanic eruptions. At least two distinctly different styles of volcanism occurred: one style formed mountains as high as 10 km with rugged surfaces, and the other style produced large paterae atop edifices with only

Aten Patera is inferred to have erupted between the two Voyager encounters, and Creidne and Svarog Paterae were identified as hot spots from IRIS data (Pearl and Sinton, 1982) and may be the site of active sulfur lakes. In the south polar region, eleven other paterae within the map area, as well as three outside it, were also identified as sites of possible volcanism on the basis of their low albedos (McEwen and others, 1985). The surface of Io is thus in a state of constant flux, and much of the surface viewed by the Voyager spacecraft will have probably changed by the time of the Galileo encounter.

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